

Fermilab



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Internship Report

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Quadrupole Magnet Inner Splice Project



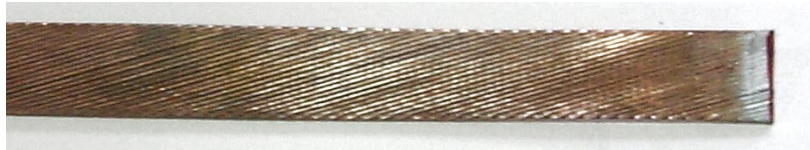
Quadrupole Magnet Inner Splice Project

Project Background

The purpose of this paper is to report the results of the Quadrupole Magnet Inner Splice Project, conducted at Fermi National Accelerator Laboratory, Batavia, Illinois in support of the LHC at CERN. CERN is the European Physics Research Laboratory in Geneva, Switzerland at which the LHC (Large Hadron Collider), a superconducting particle accelerator, is currently being built. The LHC will surpass Fermilab's Tevatron accelerator as the most powerful particle accelerator in the world.

Fermilab is working on the prototype quadrupole magnets for the Interaction Region of the LHC. Quadrupole magnets keep the particle beam tightly focussed as it travels around the ring, preventing collisions between particles and the beam tube. The IR region quadrupoles being built at Fermilab are particularly strong magnets that focus the beam as it enters the detector where the particles collide.

The IR Quadrupoles are superconducting magnets. The coils in these electromagnets are made of a Niobium-Titanium alloy cable, imbedded in copper (Picture 1). When cooled to temperatures near absolute zero, the Nb-Ti alloy lose all electrical resistance. Superconducting magnets, therefore, can achieve higher magnetic fields than conventional magnets. The IR Quadrupole has a magnetic field gradient of 240 Tesla/meter when powered to 13,800 amps at cryogenic temperatures of 1.9°K (-271.3°C, -456.3°F). The peak magnetic field in the coils is over 9 Tesla.



Picture 1

Project Overview

The superconducting Quadrupole magnets have four sets of Nb-Ti coils in a four lobe radial pattern. Each set includes two individual coils, an inner and outer coil. These two coils are connected in series with a cable splice, a solder joint of two cable ends. This splice has had a history of electrical difficulties that compromise the performance of the superconducting magnets. The splice is the only part of the coil that is not superconducting. Splice resistance can cause heating of the cable, resulting in quenches, local points at which superconductivity fails in the cable. Quenches can bring the magnet out of its superconducting state, resulting in magnet shutdown. A better understanding of how to predict when these quenches will occur at the splice is desired.

In order to gain this predictability, a non-evasive procedure to evaluate the splices is needed. This experiment will observe whether or not an electrical test at cryogenic operating temperatures can provide the proposed predictability.

Project Objective

There were four main issues to be investigated with this experiment:

- ◆ Resistance variance as a function of solder fill over area:
 - ◆ Between cable
 - ◆ Within cable between strands
- ◆ The performance difference between crosshatch joints (Figure 1a) and parallel joints (Figure 1b)

- ◆ Splice quality verification in standard splice
- ◆ Resistance vs. solder fill/thickness

Certain experiment parameters must also be maintained: test splices must be connected electrically in series, voltage feedback must be available across each splice, and each splice must be well contained and supported.

Figure 1a

Figure 1b

Layout Design

In order to maximize the results of the experiment, all the test facility capabilities must be used. The cryogenic testing platform available for testing had a maximum of 32 voltage signal inputs. Since the voltage drop across each splice needed to be recorded, the maximum splices possible per test run was 16. The next step was to design a fixture to contain the test splices.

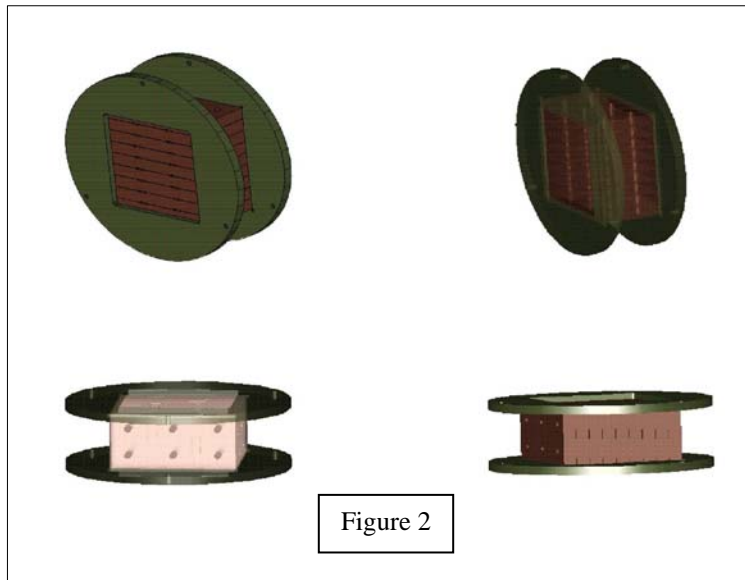
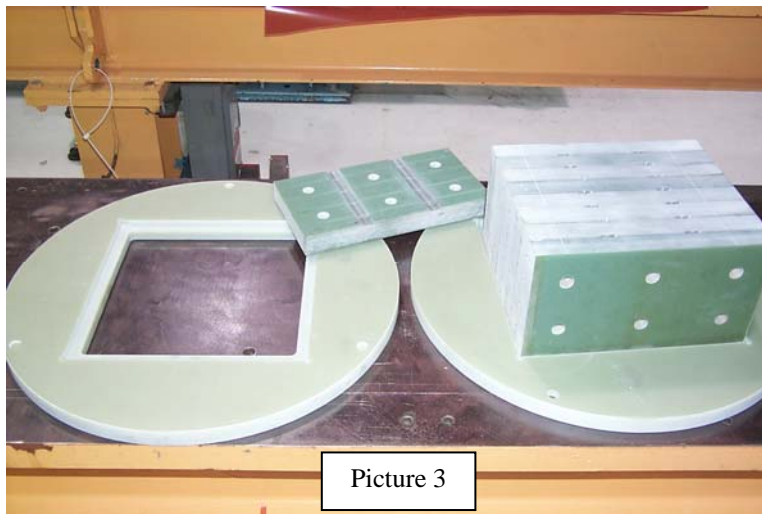


Figure 2

The model in Fig.2 was created in the I-DEAS modeling program in compliance with spatial constraints in the cryogenic testing dewar. The model was then fabricated



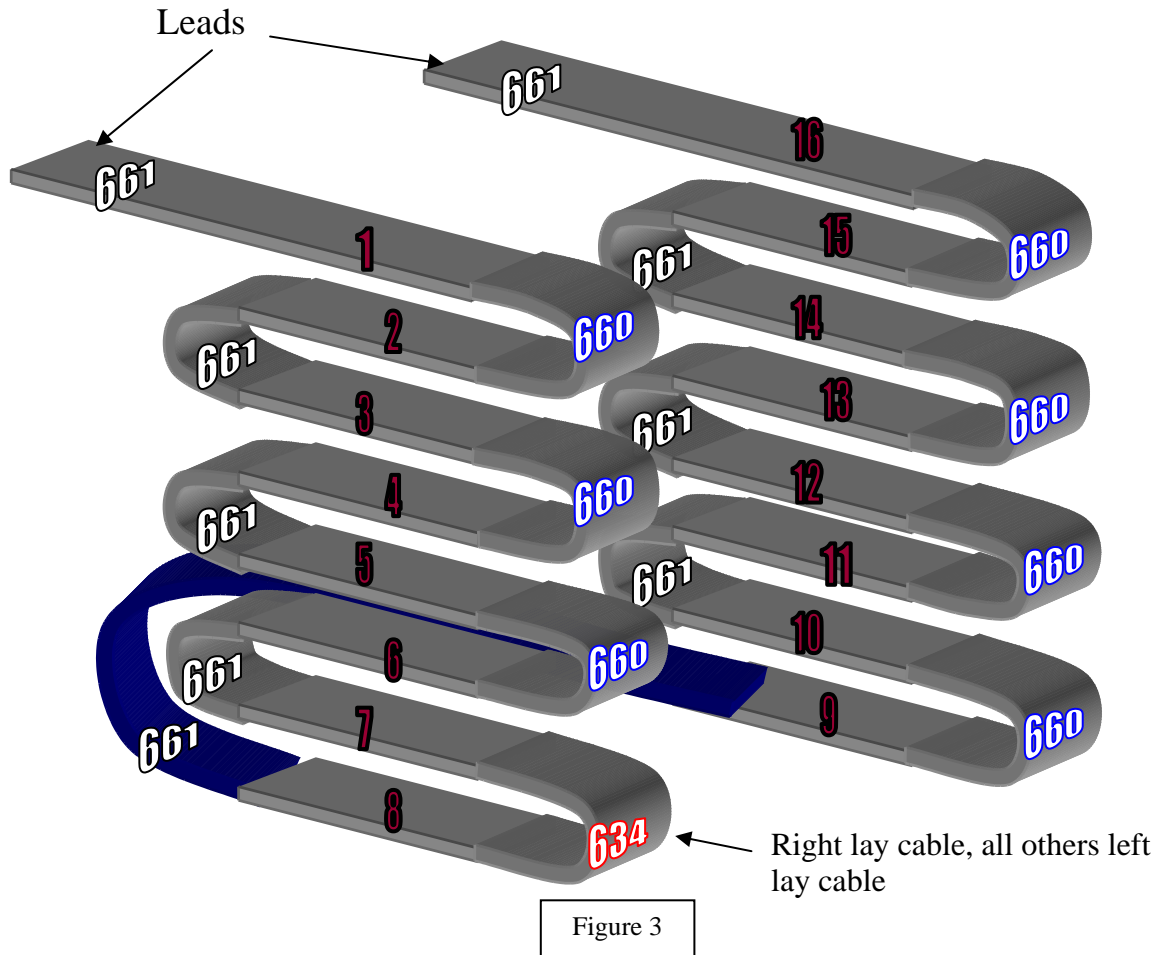
Picture 3

out of G-10, a synthetic material that is electrically non-conducting, very strong, and

performs well at cryogenic temperatures. Picture 2 shows the actual fixture. The grooves in the blocks shown in Picture 2 are for cooling the cable. The dewar was filled with liquid helium immersing the fixture to provide the cryogenic temperatures needed for superconductivity. The grooves allow the liquid to contact the splices and keep them cold.

Splice Manufacturing and Layout

The experiment fixture allows for 16 splices in unique layout. The following diagram (Figure 3) shows the orientation of the splices.



The splices are numbered 1 through 16 for convenience, and the cable types are labeled either 660, 661, or 634. These designations describe whether the cable is used for an inner coil or an outer coil, and how many strands the cable contains (Inner cable {660, 634} has 38 strands each 0.8 mm in diameter, and outer cable {661} has 46 strands each 0.65 mm in diameter). The 660 and 661 cable were wound with a left lay twist, but the 634 cable was wound with a right lay twist¹. When a splice is made with two left lay cables or two right lay cables, then the strands of the pairing surfaces create a crosshatch pattern (Figure 1a). When a splice is made with a left lay cables and a right lay cable, then the strands of the pairing surfaces run parallel (Figure 1b).

The standard splice currently used consists of 660 and 661 cable, both left lay, a 0.005-inch thick solder strip, and 100% coverage between cables (no artificial voids). The strands in this standard create a crosshatch pattern between the cables, depicted in Figure 1a. The characteristics of the experimental splices, however, were altered in several ways. The following list describes individual splice attributes.

Splice Description:

1. **Standard splice** = Solder strip, 100% coverage, [Inner cable left lay, Outer cable left lay]
2. **Standard splice** = Solder strip, 100% coverage, [Inner cable left lay, Outer cable left lay]
3. Solder strip, 50% kapton coverage **between** cables (horizontally), [Inner cable left lay, Outer cable left lay]
4. Solder strip, 50% kapton coverage **between** cables (horizontally), [Inner cable left lay, Outer cable left lay]
5. Solder strip, 50% kapton coverage **between** cables (vertically), [Inner cable left lay, Outer cable left lay]
6. Solder strip, 50% kapton coverage **between** cables (vertically), [Inner cable left lay, Outer cable left lay]
7. Solder strip, 100% coverage, [Inner cable **right** lay, Outer cable **left** lay]
8. Solder strip, 100% coverage, [Inner cable **right** lay, Outer cable **left** lay]
9. Solder strip, 50% kapton coverage **inside** Inner cable, [Inner cable left lay, Outer cable left lay]
10. Solder strip, 50% kapton coverage **inside** Inner cable, [Inner cable left lay, Outer cable left lay]
11. Solder strip, 50% kapton coverage **inside** Outer cable, [Inner cable left lay, Outer cable left lay]
12. Solder strip, 50% kapton coverage **inside** Outer cable, [Inner cable left lay, Outer cable left lay]
13. Solder strip, 50% kapton coverage **inside both** Inner and Outer cable, [Inner cable left lay, Outer cable left lay]
14. Solder strip, 50% kapton coverage **inside both** Inner and Outer cable, [Inner cable left lay, Outer cable left lay]
15. **No** solder strip, 100% coverage, [Inner cable left lay, Outer cable left lay]
16. **No** solder strip, 100% coverage, [Inner cable left lay, Outer cable left lay]

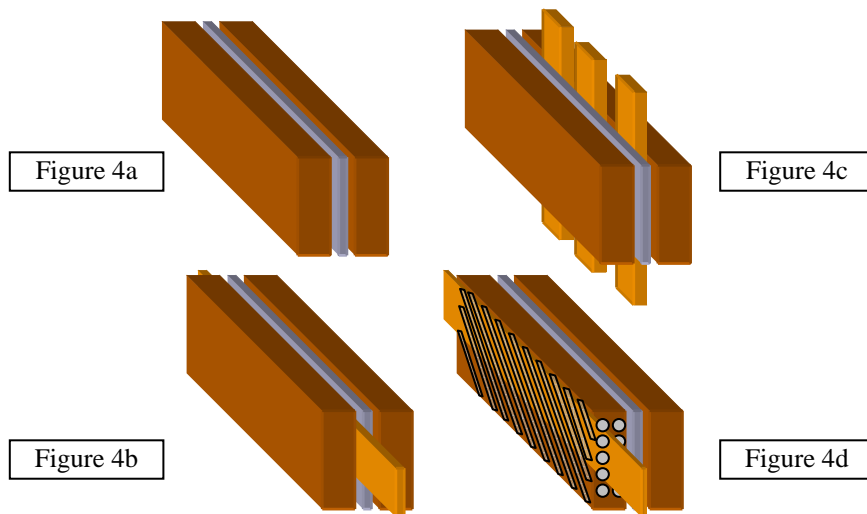
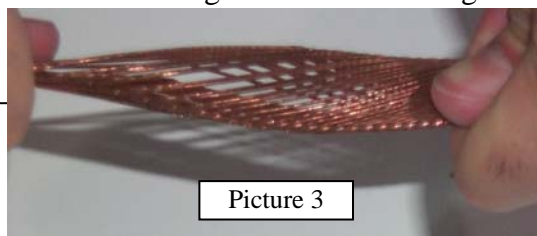


Figure 4a depicts the standard magnet splice with the solder strip and two cables, the same splice as in Splices 1 and 2. Figure 4b shows the configuration of splices 3 and 4, Figure 4c illustrates splices 5 and 6, and Figure 4d explains splices 9 through 14.

To gain a better understanding of the electrical signature of “bad” splices, several



Picture 3

irregularities were added to the splices. Splices 3 through 6 had pieces of 0.001" thick kapton strip between the cables inside the solder joint to simulate no contact cable-to-cable. Splices 9 through 14 had pieces of kapton inside the individual cables. This would simulate no contact strand-to-strand. Picture 3, shows how the cable opens when twisted and allows access between the strands.

These magnet splices are fabricated with pre-tinned cable ends and a heating fixture. The two ends are placed inside the fixture, fluxed, torqued into place, and heated up until the 0.005" solder strip placed in between the cable melts thoroughly, approximately 560°F. Splices 15 and 16, however, did not have a solder strip added to the splice and relied solely on the pre-tinning of the cable ends for the joint.

Splice Testing

To test the splices, a cryogenic chamber adapted for high power data acquisition (DAQ) was used. The assembled splice fixture was attached to the testing fixture as well as the power leads (Pictures 4a,b). These power leads supply the 5000 amperes used in the experiment. Once placed inside the test stand chamber, the whole dewar was cooled down with liquid Helium to 1.9°K.

Using the voltage tap wires attached at both ends of each splice, voltage data was collected using a Hewlett Packard 3458 digital voltmeter (DVM). Data was integrated



Picture 4a



Picture 4b

over 48 line cycles. Current controlled power was supplied at 500 amp intervals, ramping from 0 amps to 5000 amps, and then immediately to 0 amps again (Figure 5).

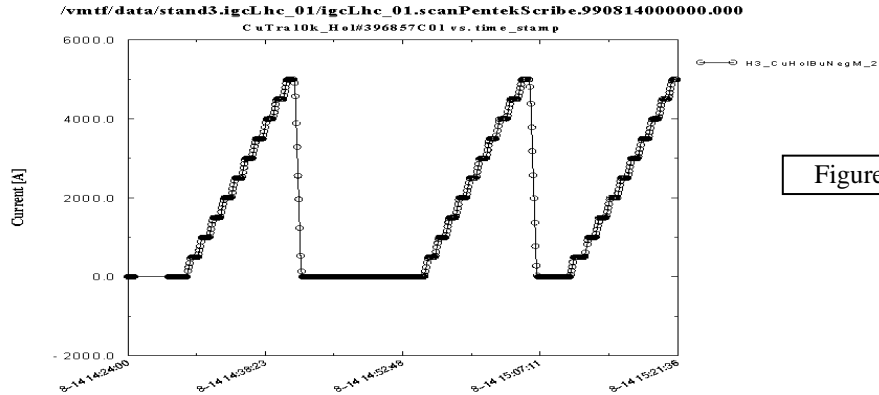


Figure 5

This ramping of power allowed acquisition of enough voltage data to calculate an electrical resistance for each individual splice. The voltage of each splice was plotted against current and a linear regression curve was calculated (Figure 6). The slope of this line is directly the resistance of the splice from Ohm's law, $\varpi = I\rho$. The resistance values are shown in Table 1.

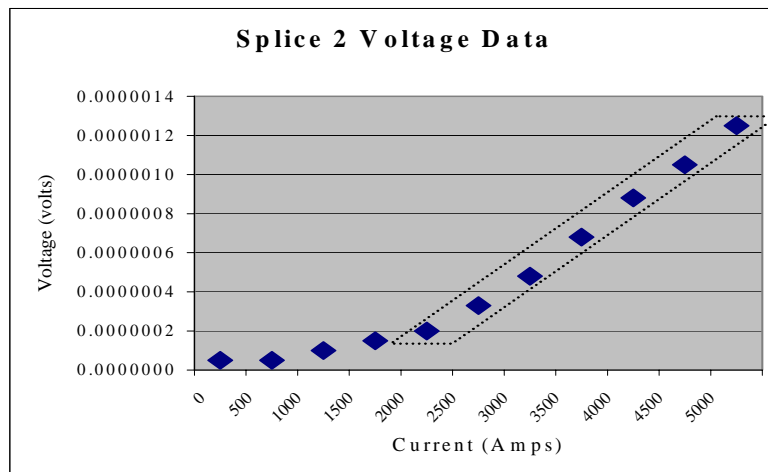


Figure 6

| Table 1: Splice Resistance | | | | | |
|----------------------------|-----------------------------|--|----------|-----------------------------|--|
| Splice # | Resistance ($\eta\Omega$) | | Splice # | Resistance ($\eta\Omega$) | |
| 1 | N/A | | 9 | 0.39 | |
| 2 | 0.36 | | 10 | 0.38 | |
| 3 | 0.61 | | 11 | 0.41 | |
| 4 | 1.37 | | 12 | 0.48 | |
| 5 | 0.7 | | 13 | 0.47 | |
| 6 | 0.58 | | 14 | 0.38 | |
| 7 | 0.26 | | 15 | 0.44 | |
| 8 | 0.23 | | 16 | 0.5 | |

Analysis & Conclusion

Comparison of the resistance values for the various splice configurations indicates several things. The following list describes these deductions.

- 1) Voids between strands are not critical and pose no real problem
- 2) Voids between cable are critical and need to be eliminated or controlled
- 3) Solder strip in splice favorable over using no solder strip
- 4) Right lay cable, left lay cable combination seems favorable

Deductions 3 and 4 require more investigation to determine relevance. Conclusion 2 seems very reasonable and verifies previous concepts.

Recommendations

In order to validate the earlier conclusions, I recommend that a second test be completed to verify the relationship between crosshatch and parallel strand configurations. A second batch of splices has already been manufactured and is ready for testing. This batch consists of 6 Right lay / Left lay cable splices and 6 Left lay / Left lay splices, all with 100% solder fill.

A third test is also recommended to investigate the relationship between the solder strip thickness and splice quality and electrical resistance. The initial findings show that the splices with solder strips performed better than the splices without solder strips. This thickness could be optimized for splice performance.

These tests should then provide a full understanding of the different parameters that describe Quadrupole magnet splices.

Footnotes:

¹ The difference between left lay and right lay cable is the direction of twist. The cable is made up of many strands twisted together. A right lay cable is wound clockwise like a right-handed screw thread, left lay is wound the opposite direction. This controls the pattern of cable-to-cable interface, whether the cables in a splice make a crosshatch pattern or the strands line up parallel to each other. An objective of this experiment is to determine which format is optimum.